Journal of Membrane Science and Research 10 (2024) 2000889

Journal of Membrane Science & Research

journal homepage: www.msrjournal.com

Review Paper

Geopolymer and Alkali-Activated Membranes Opportunities and Assessment of Performance

Amal Magdy El-Sayed [1,*], Heba Mohamed Abdallah [2], Mahmoud Abdel-Goad [3], Reda Abobeah [3], Shereen Kamel Amin [2]

[1] *Chemical Engineering Department, Egyptian Academy for Engineering and Advanced Technology (EA&EAT) affiliated to Ministry of Military Production, Km# 3 Cairo- Belbeis Desert Road, Cairo, Egypt*
[2] *Chemical Engineering and Pilot Plant Department, Engineering and Renewable Energy Research Institute, National Research Centre (NRC), 33 El-Bohouth St. (Former El-Tahrir St.), Dokki, Giza, Egypt*
[3] *Department of Chemical Engineering, Faculty of Engineering, El-Minia University, El-Minia, Egypt*

Article info

Received 2023-04-03
Revised 2023-11-04
Accepted 2023-12-02
Available online 2023-12-02

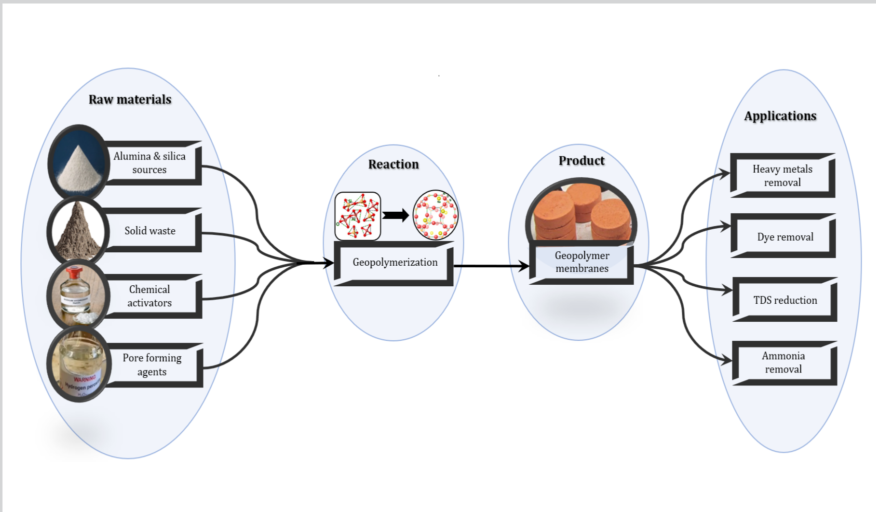
Keywords

Chemical activation
Geopolymerization
Inorganic membrane
Solid waste management
Water treatment

Highlights

- Geopolymer membranes have several advantages compared to other membranes.
- Geopolymer membranes can be manufactured in an eco-friendly way.
- Raw materials and operating conditions have a direct effect on the produced membrane.
- Geopolymer membranes are used in several applications and show high efficiency.

Graphical abstract



Abstract

Waste generation issue is considered a major problem, especially with the high rate of population growth. This matter doesn't include only municipal waste, it also extends to the industrial effluents that are produced in huge amounts. These pollutants affect natural resources and change the properties of soil, water, and air. The undesirable environmental impact is maximized when the effluent is non-biodegradable, such as construction and demolition waste, fly ash and, blast furnace slag in the case of solid waste, and wastewater contaminated with heavy metals or dyes in the case of liquid waste. Accordingly, waste management techniques are applied to mitigate or reduce the hazardous impact on the environment. In this manner, solid waste is recycled to produce alkali-activated membranes that are used to eliminate the undesirable constituents in wastewater. Alkali-activated membranes are inorganic membranes manufactured using kaolin or metakaolin as the main raw material in addition to fly ash or blast furnace slag. In order to fabricate these membranes, a variety of raw materials, chemical activators, pore-forming agents, curing time, and curing temperature may be applied, then the product is tested to make sure that it will withstand the operating conditions. In this paper, different fabrication parameters of alkali-activated and geopolymer membranes and their effect on product properties are illustrated.

1. Introduction

Waste is generated in huge amounts and affects the environment negatively. It is generated in several forms such as solid, liquid, and gas emissions. Solid waste generation has become an important issue in recent years, particularly in developing countries. Agricultural waste, industrial waste, hazardous waste, construction and demolition waste (CDW), and municipal solid waste are the different types of solid waste. As

* Corresponding author: amal.magdy@eaeat.edu.eg (A. M. El-Sayed)
DOI: 10.22079/JMSR.2023.2000889.1607

illustrated in Table 1, Egypt produced around 90.76 million tonnes of solid waste in 2016, from which approximately 5.8 million tonnes are designated CDW [1]. CDW typically contains 40 - 50 percent concrete and bricks, 20 - 30 percent wood, and the remaining 20 - 40 percent is made up of miscellaneous components such as metals, glass, insulation materials, and electrical parts [2].

Table 1
Solid waste categories [1]

Solid waste categories	Amount of waste, million ton
Agricultural waste	31
Channels and drain cleaning	25
Municipal solid waste	21
Construction and demolition waste	5.8
Industrial waste	4.9
Sludge	2
Hazardous waste	0.54
Medical waste	0.52

On the other hand, about 40% of the global population suffers from water scarcity from which about 783 million people can't find pure water. Accordingly, water scarcity doesn't happen due to water shortage only, but also as a result of water pollution that affects water quality delivered to people. These problems become a real danger, especially with the current frequency of population growth that increases very rapidly [3]. It is known that the water poverty limit for achieving self-sufficiency in drinking, agricultural, and industrial uses is 1000 cubic meters per capita. According to this definition, Egypt is considered one of the countries that suffer from water poverty, as in 2017, the population was about 92 million people, while the usage this year was about 80.25 billion cubic meters, which is considered lower than the poverty level [4].

Wastewater can be defined as water that has altered physical, chemical, or biological characteristics due to its application in domestic, agricultural, or industrial purposes. In Egypt, the industrial sector consumes about 5.36 billion cubic meters annually from freshwater supplies, while the amount of wastewater released to the Nile River is about 1.38 billion cubic meters per year [5]. Fig. 1 shows the industrial contribution to water pollution as water may be contaminated with microorganisms, detergents, fertilizers, dyes, or heavy metals, so wastewater treatment procedures become a must before discharge or recycling to be used for another purpose [6].

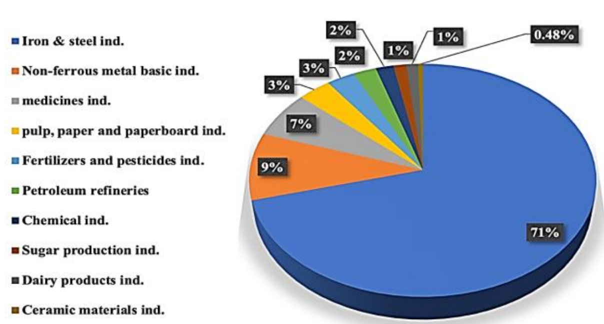


Fig. 1. Industry contribution percent in total water pollution load

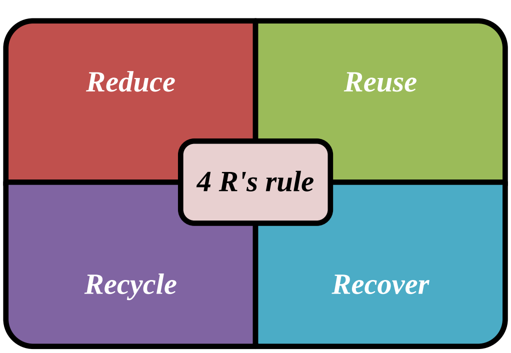


Fig. 2. Four R's rule for waste management

To mitigate the amount of waste generated one or more of the four R's rule of waste management techniques are applied to mitigate this hazard. This rule summarizes the main techniques followed worldwide to protect the environment which are reduction, reusing, recycling, and recovery. The order in which these techniques are considered is from the top to the bottom of the hierarchy as shown in Fig. 2 [7]. At first, several trials are performed to prevent or reduce the amount of waste generated from the source itself, and then the waste is reused or recycled, if possible, while energy recovery is only available in the case of organic wastes. Finally; the residual amount of waste should be dumped in an environmentally friendly way [8].

In this manner, the purification of wastewater is a considerable solution to the water shortage problem. Consequently, different applications and treatment steps are applied, such as coagulation and flocculation, chemical precipitation, adsorption, and membrane separation. One of the most commonly used applications in water and wastewater treatment is membrane separation technology [9].

2. Membrane Separation Technique

Membranes are filters designed with selective layers to be able to separate different materials concerning particle size. They are generally applied for separation, purification, and concentration of mixtures, while the most common applications are water and wastewater treatment [10,11].

2.1. Advantages of Membrane Separation Technology

Membranes have several advantages that characterize this way and allow it to be the most widely used application in different applications such as [10,12–16]:

- Low energy consumption when compared with thermal separation processes, as thermal techniques depend on successive evaporation/ condensation to eliminate the not-required substances.
- Suitable for heat-sensitive materials, where they may be used in the ambient temperature
- No change in the chemical composition of the filtered materials, consequently it doesn't need further purification
- It requires a simple device with easy operation, control, and maintenance
- High separation efficiency due to its high selectivity

2.2. Membrane Classifications

The main factors affecting membrane fabrication are the mechanical strength of the produced membrane to be able to withstand the applied pressure and the pore size that controls membrane selectivity. Thus, they are classified based on the raw materials from which they are fabricated into organic and inorganic membranes. Organic membranes are mainly fabricated from polymeric materials, while inorganic membranes may be ceramic or metallic membranes. The inorganic membranes become dominant due to their chemical, mechanical, and thermal stability. Also, their fabrication from different oxides and sintered materials allows them to withstand various regeneration techniques using chemical reagents or by applying pressurized water [3]. They also may be categorized based on pore size into Microfiltration (MF), Ultrafiltration (UF), Nanofiltration (NF), and Reverse Osmosis (RO) as shown in Table 2 [3,17].

Ceramic membranes are commonly fabricated through pressure-driven processes, in which high pressure is applied in one direction causing a reduction in pore size. This reduction affects the permeability of flow and selectivity as well. Also, to get the required mechanical strength and porosity, the product is sintered at a high firing temperature. Consequently, high carbon dioxide emissions have evolved affecting the environment badly and increasing the negative impact of greenhouse gases [18]. To overcome the drawbacks of ordinary ceramic membranes, a new trend in the fabrication of inorganic membranes has been developed, in which inorganic membranes may be fabricated by recycling solid waste after chemical activation through a geo-polymerization reaction.

Table 2
Membrane categories [17]

Category	Pore size	Driving force	Mechanism	Particles removed	Industrial applications
Micro-filtration	< 10 µm	1 – 5 atm	Sieving	- Microorganisms	- Solid-liquid extraction - Separation of oil-water emulsions - Beverage and pharmaceutical industries - Biological treatment of wastewater - Pre-filters to remove large particles
Ultra-filtration	< 0.05 µm	2 – 10 atm	Sieving	- Suspended solids - Viruses - Bacteria - Macromolecules	- Separation of oil-water emulsions - Fruit juice clarification - Milk and whey production - Pharmaceutical's purification - Potable water production - Secondary or tertiary wastewater treatment
Nano-filtration	< 1 nm	5 – 50 atm	Sieving	- Dissolved salts - Most organic molecules - All viruses	- Water treatment processes for softening hard water and color removal
Reverse Osmosis	< 0.1 nm	10 – 100 atm	Solution diffusion	- Minerals - Monovalent ions	- Seawater desalination - Fruit juice concentration - Cheese whey concentration - Ice-making - Car wash water reclamation
Electro-dialysis	Electrically charged membranes	Electrical potential	Electrostatic diffusion	- Dissolved salts	- Water treatment - Recovery of materials in effluent streams

3. Alkali-Activated Materials and Geopolymer

They are crosslinked structures innovated recently using chemically activated aluminosilicate materials to produce new materials with high mechanical strength that reach hardening rapidly. They have two categories according to the ratio between silicon and calcium (Si/Ca ratio), high calcium systems that form calcium-aluminum-silicate-hydrate gel and low calcium systems that form sodium-aluminum-silicate-hydrate gel. The high calcium system depends on fly ash (class C) and blast furnace slag as the main raw materials besides metakaolin, while the low calcium system depends mainly on fly ash (class F). The low calcium system is also known as geopolymer [19,20].

The word "geopolymer" is composed of two parts; "geo," which denotes that the substance is obtained from the ground, and "polymer," which is considered the result of the combination of some monomers. Generally; polymers are defined as organic materials composed mainly of carbon atoms as they can share with similar or different atoms up to four electrons. In the case of polymerization; it gains one, two, or three electrons from these different atoms, and the rest of the electrons required to reach stability are taken from a carbon atom and so on. In the same way; silicon combines with four oxygen atoms to fill its outer orbit leaving negative charges to be able to combine with another molecule [21].

In 1984, the produced slag from the blast furnace of iron – which is considered waste from the iron industry – was treated with some alkalis, and then it was added to the Portland cement. The product is characterized to determine its setting properties and the rate at which hardness occurs, and it was found that this new binder shows rapid hardening. At the beginning of the 6th decade in the last century; this process was performed using sodium chloride (NaCl) and sodium hydroxide (NaOH) as activating agents to produce alkali activated slag cement. By the end of that decade, sodium and calcium hydroxides were applied as solidification reagents, as they react with clay minerals (aluminates and silicates) to produce sodium and calcium aluminosilicate hydrates [21].

3.1. Geopolymerization Reaction

It is a reaction that occurs between a solid material and a liquid chemical activator. The solid material should be a reactive aluminosilicate material such as metakaolin, fly ash, blast furnace slag, etc. The most commonly used aluminosilicate source is metakaolin which is obtained by calcination of kaolinite. Clay that is mostly made up of kaolinite ($Al_2Si_2O_5(OH)_4$) is calcined at temperatures between 600 and 900˚C to produce metakaolin ($Al_2Si_2O_7$) as a result of the de-hydroxylation reaction as illustrated in the equation (1) [22,23].

$$Al_2O_3.2SiO_2.2H_2O \xrightarrow[600\text{–}900°C]{Calcination} Al_2O_3.2SiO_2 + 2H_2O \qquad (1)$$

The next step involves adding alkali hydroxide to the mixture of metakaolin and water to trigger a reaction that creates a three-dimensional geopolymer with an amorphous or semi-crystalline structure. The chemical activator is an alkaline solution usually sodium hydroxide (NaOH) or potassium hydroxide (KOH). It is selected according to several factors, such as the cost of production, heat evolved due to dissolution, viscosity, and availability [22,23].

The polymerization process of aluminosilicate is considered a polycondensation reaction. Polycondensation is a chemical condensation process to produce a polymer by linking monomers to form long chains releasing water or a similar simple substance. In the case of geopolymer, aluminosilicate forms a suspension in the alkaline solution forming an intermediate gel phase with a disordered structure, then polymerization occurs after the reorganization of monomers. The final step is the hardening that happens after a suitable curing time due to water evaporation as shown in Fig. 3 [24,25].

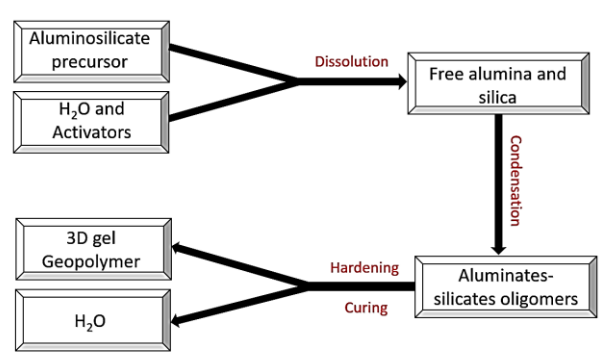


Fig. 3. Reaction mechanism of the polymerization process

Geopolymer materials are characterized by high pH due to applying the alkali solution that helps accelerate the process, and the ratio between raw materials causes changes in chemical, mechanical, and thermal properties of the generated materials due to the change in the microscopic structure of the product as shown in Table 3 [24,25]:

Table 3
The effect of the ratio between silica and alumina on geopolymer structure [24,25]

Silica-alumina ratio	Geopolymer name	Chemical structure
Si/Al = 1:1	Poly(sialate)	(−) (−Si−O−Al−O−) with O below Si and Al
Si/Al = 2:1	Poly(sialate-siloxo)	(−) (−Si−O−Al−O−Si−O−) with O below each Si and Al
Si/Al = 3:1	Poly(sialate-disiloxo)	(−) (−Si−O−Al−O−Si−O−Si−O−) with O below each Si and Al

Table 4
Main elements present in different classes of fly ash [21]

Oxides types	Class F (%)	Class C (%)
CaO	< 10 (1.3 – 4.1)	>10 (13.9 – 49)
SiO_2	47.2 – 54	18 – 24.8
Al_2O_3	27.7 – 34.9	12.1 – 14.9
Fe_2O_3	3.6 – 11.5	6.3 – 8.7
Other oxides*	2.4 – 10.7	8.9 – 16.9

*The other oxides may be magnesium, sodium, potassium, and sulfur [21].

3.2. Advantages of Geopolymer and Alkali-Activated Membranes

Geopolymer and alkali-activated membranes have several advantages over the ordinary ceramic membranes such as [22,27]:

1. Consumption of construction wastes, such as silica and alumina are considered their main raw materials.
2. After small curing periods; the strength reaches higher values than that of the ordinary building materials due to the high alkalinity of the applied solution.
3. Having good resistance to chemical attack.
4. Having good durability.
5. Reduction in energy consumption and consequently the emissions of greenhouse gases are reduced.

3.3. Raw Materials of Geopolymer and Alkali-Activated Membranes

Different types of raw materials may be used for the production of geopolymer and alkali-activated membranes. These materials should be rich in silica and alumina such as clay or metakaolin, but to keep this production beneficial economically, and environmentally friendly, waste materials are crushed, ground, and blended with metakaolin using an alkaline activation solution to form a membrane with acceptable properties [28–30]. In the following paragraphs; different raw materials for geopolymer production and their sources are illustrated.

3.3.1. Fly Ash

Fly ash is defined as a waste material produced in the form of fine particulates through the combustion process of coal. From this definition, it is clear that it is produced in too high amounts due to the large-scale use of coal in power generation worldwide [31]. It is usually disposed of in landfills, but it causes fatal effects on the environment due to the leaching of heavy metals in soil and groundwater besides the large area requirements for landfilling [32]. It is shown in Fig. 4 that about 25% of the annual production of fly ash is utilized, while the rest is still a source of hazard [33,34].

Generally; coal is categorized according to the degree of conversion of the vegetable source into coal into high-rank coal with a black color and low-rank coal with a brown color [35]. The American Society for Testing and Materials (ASTM) classifies fly ash into two types according to the category of coal from which it is generated [31,34]. Class F is the most common one as it is generated from high-rank coal, while class C is the residue from low-rank coal [35]. Both of them consist of the same elements but with a different chemical composition which mainly appears in the percentages of calcium, silicon, aluminum, and iron oxides as shown in Table 4, but the most common oxide that differentiates between the two types is the calcium oxide, as it exists with percentage higher than 10% in class C, while in class F its percentage is very low [21,31,33–35].

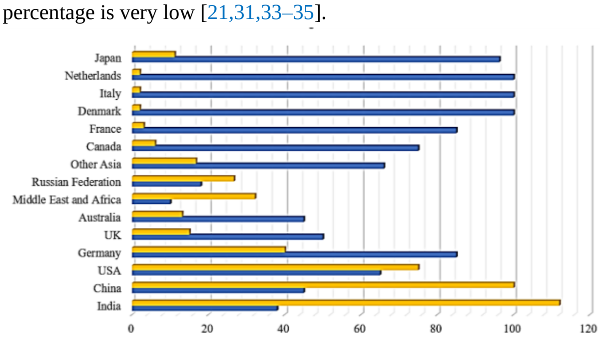


Fig. 4. The global production of fly ash and the utilization percent in each country

Fly ash is widely used in alkali-activated membranes and it shows high removal efficiency besides its excellent mechanical properties. Panyang He et al. used fly ash as the main raw material to generate a membrane to be applied in oil removal from water. They found that the separation efficiency was very high and exceeded 98% [36].

3.3.2. Blast Furnace Slag

The iron production process is a process performed in the blast furnaces at a very high temperature of about 1500˚C by mixing iron ore with both coke and limestone to produce molten iron as a main product and blast furnace slag as a by-product. Slag is considered a by-product as it is produced in very large amounts where every ton of iron is accompanied by about 200 – 400 kg of slag. The density of slag is lower than that of iron, so it is considered a useful material that prevents oxidation of iron as it forms a top layer above the molten iron in a furnace. It is generated as a result of the combination of non-metallic materials that react with iron ore to produce the main product. These materials are mainly silicon, aluminum, calcium, and magnesium oxides, so it is usually incorporated in the manufacturing of construction materials such as cement and building blocks. Blast furnace slag is generated in the molten form, so it should be cooled to be used in further applications. There are several ways for cooling and solidification of molten slag each of them produces a special type of slag as shown in Table 5 [37].

Generally; blast furnace slag is considered the most ancient additive in the generation of geopolymeric materials as discussed previously due to the presence of silica, alumina, and lime as the main components [21]. These components give it the hydraulicity that allows it to be used in the manufacturing of membranes [38]. The performance of alkali-activated blast furnace slag is examined through the removal of COD and water from ethanol [39,40].

3.3.3. Red Mud

The Bayer process is a hydrothermal reaction in which alumina is extracted from bauxite ore. In this process, bauxite is treated using caustic soda at elevated temperatures to eliminate the undesired solid materials that are called red mud. Red mud is rich in alumina, silica, iron oxide, and calcium oxide, so it is widely applied in the manufacturing of ceramic materials [41–43]. Red mud is generated in large amounts, as the production of one ton of alumina is accompanied by various quantities of red mud ranging from 0.5 to two tons according to the chemical composition of bauxite [44]. Now, it is widely used in the preparation of alkali-activated membranes because of its chemical composition which enhances the properties of the product [45,46].

3.3.4. Silica Fume

It is a by-product from an electric arc furnace during the production of silicon in its elemental form or silicon alloys such as ferrosilicon alloy using high-purity quartz. This process occurs by the reduction of quartz using coal at about 2000℃ to produce silicon that reacts with oxygen to form silicon dioxide vapor. Silicon dioxide vapor is condensed when temperature decreases to produce very fine spherical particles with particle diameters ranging from 0.1 to 0.3 μm called silica fume, micro-silica, or silica dust [47,48]. The handling of these particles is very difficult, so they are commonly handled in the form of water slurry. Silica fume is an amorphous structure with silica content ranging from 85% to 95% according to the source and type of alloy produced [47,49]. For this reason, silica fume is applied in alkali-activated membranes to enrich the material with silica, also it is provided as a pore-forming agent [50,51].

Table 1
Classifications of Blast furnace slag [37]

Type	Method of cooling and solidification	Properties	Applications
Granulated	Rapid quenching using high-pressure water jets	Its particle size is less than 5mm and may be ground to be used in further applications	Ordinary cement
Air-cooled	Open pits under atmospheric conditions	Crystalline Hard material High density	Road pavement
Expanded	Mechanically using a small amount of cooling water	Lightweight	Building bricks Light concrete

3.4. Effect of Preparation Parameters on Membrane Properties

The application of different raw materials, chemical reagents, and pore-forming agents besides the change in preparation parameters are studied in several publications to determine their impact not only on the mechanical properties of the membrane but also on the rejection percent of different contaminants.

3.4.1. Silica to Alumina Ratio

Martine Youmoue et al. used metakaolin as the main raw material and applied silica fume to adjust the Si/Al ratio besides being a pore-forming agent. After the preparation of several samples with various additives it was observed that, when the Si/Al ratio increases, porosity increases, and consequently permeability increases leading to higher removal of methylene blue dye from water. While compressive strength decreases due to poor polycondensation [52]. This observation is demonstrated in another publication, using blast furnace slag as the raw material and it is concluded that, as the Si/Al ratio increases up to 2.6, the compressive strength increases, but when the ratio exceeds this value, excess silica becomes ineffective and hence compressive strength begins to decrease [51].

3.4.2. Activator Concentration

The type of activator and its molarity affect the compressive strength. In this manner, fly ash-based membranes were prepared after activation using sodium silicate/sodium hydroxide solution with a mass ratio equal to 2.5:1. By comparing the results obtained from the publication of Pavithra Parthasarathy et al. and that of Saeed Gul et al., it was found that as the molarity of NaOH increases, the compressive strength decreases [53,54]. The effect of the presence of hydroxide ion was taken deeply into consideration through the research done by Pavithra Parthasarathy et al. and it was observed that compressive strength increases with increasing the molarity of NaOH, however after a certain limit, the strength begins to decrease. This happened because of the rapid precipitation of aluminosilicate gel which leads to fast hardening and stops the geopolymerization reaction preventing some precursors from forming and causing a negative impact on the mechanical strength [53].

Other publications tried to study the concentration of activators using metakaolin-based membranes and it was found that the samples prepared using 10M NaOH and Na_2SiO_3: NaOH equals 1.5 reached 41.46 MPa compressive strength [55]. While using 18M NaOH and Na_2SiO_3/NaOH with a molar ratio of 4.3, the compressive strength improved and reached about 62 MPa [56]. This phenomenon occurs as alkali-activated systems require the addition of soluble silicate up to the saturation level to get the final physical and chemical properties of the product. To maintain silicates soluble in the paste and to activate the aluminosilicate precursor, high alkalinity medium is essential [57].

3.4.3. Pore-forming agent

The percentage of pore-forming agents has an obvious effect on compressive strength, porosity, pore size distribution, and consequently membrane performance. Xue-min Cui et al. used hydrogen peroxide as a pore-forming agent and studied the impact of increasing its percentage from 0.7 to 1.1% on compressive strength and the results showed that the compressive strength was affected negatively, as it decreased by about 69.5% [58]. Also, Tee Tan et al. compared the pore size of two samples. The first one is non-foamed and the second one is foamed using 1.2 wt% hydrogen peroxide (H_2O_2) as a pore-forming agent. The results showed that, in the case of non-foamed samples, the micropores are the dominant as pore size ranges from 9 – 40 nm with an average pore size of 17.58 nm. In the case of the foamed sample the pore size distribution has a wide range and the pores are not consistent due to the existence of both micro and macropores, so the average pore size increases apparently and becomes 56.47 nm. Also, increasing the percentage of pore-forming agents allows the combination of pores-forming channels inside the membrane that are controlled according to the constituents that should be eliminated [59].

On the other hand, the type of pore former also changes the properties of the geopolymer membrane. Amir Khattak et al. tried to apply hydrogen peroxide and starch separately as pore formers with percentages ranging from 0 to 15%. They concluded that, after evaporation of hydrogen peroxide, the pore size increased up to 6.6 μm, while in the case of starch pore size increased up to 3.45 μm. Thus, the samples prepared using H_2O_2 have lower compressive strength than the samples prepared using starch. Also, the porosity in the case of H_2O_2 is higher than that in the case of starch [60].

3.4.4. Water Content

Increasing the initial water content or water/ solid ratio is desired to provide high porosity and, in some cases, large pore size, but it affects the surface area negatively. Throughout dehydration, high water content causes channels in the membrane which affect the strength of the membrane and decrease the surface area exposed to contaminated medium. This effect was studied by Xuemin Cui et al. and it was found that increasing the H_2O/Na_2O ratio from 18 to 22 decreases the surface area from 37.8739 to 2.8522 m^2/g [61].

3.4.5. Curing Temperature

The activation temperature is a critical factor in the fabrication of alkali-activated membranes. It was studied in several publications where metakaolin is used as a silica/alumina source and sodium silicate/sodium hydroxide mixture is applied as a chemical activator. Xuemin Cui et al. found that the compressive strength is 18.67 MPa when the activation is performed at 60℃ [61], while Saeed Gul et al. achieved high values of compressive strength up to 62 MPa when the samples were exposed to hydrothermal treatment at 90℃ [56]. This obvious increase in compressive strength with increasing the curing temperature is due to the effect of temperature on the rate of reaction which causes rapid hardening and increases the probability of the interaction between particles, so geopolymerization occurs properly [62].

3.4.6. Curing Time

Zhang et al. and Pavithra Parthasarathy et al. studied the effect of varying curing times on the mechanical strength of the final product. They found that, as time increases, the reaction proceeds yielding a harder product [53,63].

3.5. Effect of pH of The Medium and Concentration of Contaminants

From the previous studies, it was found that the pH value of the medium and the initial concentration of contaminants affect the rejection percentage strongly. As described by Yao Jun Zhang et al. and G. Pugazhenthi et al. the removal percentage of contaminants depends mainly on the chemical form of the salt or heavy metal to be removed. For example, chromium compounds are ionized in water in different forms as they may exist in the form of $HCrO_4^-$, CrO_4^{2-}, or $Cr_2O_7^{2-}$. In this context, the most favorable pH range for the removal of $HCrO_4^-$ is the acidic medium with a pH range of 1- 6.5, and CrO_4^{2-} requires a basic medium with pH greater than 8, while for concentrations of Cr(VI) more than 10^{-3} M, $Cr_2O_7^{2-}$ exists with $HCrO_4^-$ [64,65].

4. Conclusion

Currently, the waste generation issue is the main problem worldwide, and its hazard maximizes with the rapid population growth. Thus, the reduction, reusing, recycling, and recovery are considered the golden rules to mitigate this problem. Water and wastewater treatment are essential to overcome water shortage, so several techniques are applied to improve water quality. Between these techniques, membrane separation technology especially using inorganic membranes becomes one of the promising techniques due to its ability to withstand chemical attack, easily deal with the heat sensitive materials, and its high selectivity. Besides the many advantages of inorganic membranes, it still requires high fabrication costs due to the high sintering temperature required. Consequently, geopolymer membranes surpass ordinary inorganic membranes as their fabrication is performed under low temperatures. Also, it may be manufactured using solid waste as raw materials to reduce the negative impact of this waste on the environment.

It is concluded that the preparation parameters have a great impact on the physical and mechanical properties of the membrane as summarized below:

- Si/Al ratio influences the mechanical properties of alkali-activated membranes as the addition of Si increases the compressive strength and decreases the porosity. While excess amount of silica causes a negative impact on the mechanical properties due to the excess is not effective causing low polycondensation.
- High alkalinity improves the properties of the membrane as it allows silicate to be soluble in the paste until it reaches the required properties of the membrane.
- A pore-forming agent is provided to enhance the porosity, but it affects mechanical strength negatively, so its concentration is adjusted to control the pore size.
- Initial water content is a critical factor as it is important for the workability of the prepared sample, but it influences both surface area and compressive strength of the membrane badly. Thus addition of water is adjusted to control the porosity.
- Compressive strength increases as curing temperature and curing time increase due to the progress that occurs in geopolymerization reaction causing hardening.

CRedit authorship contribution statement

A.M. El-Sayed: Data curation; Writing - original draft; Formal analysis
H. M. Abdallah: Supervision, Conceptualization
M. Abdel-Goad: Supervision, Review & Editing
R. Abobeah: Supervision, Review & Editing
Sh. K. Amin: Supervision, Conceptualization; Review & Editing

Funding sources

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data are available upon request.

References

[1] N. Yousif, S. Abdel Rahim, S. Saleh, Egypt-SOE-2016-FINAL, (2016). https://www.google.com/search?client=safari&rls=en&q=Egypt-SOE-2016-FINAL&ie=UTF-8&oe=UTF-8 (accessed January 12, 2023).
[2] G. Tchobanoglous, Other Special Wastes: Construction and Demolition (C&D) Debris, in: G. Tchobanoglous, F. Kreith (Eds.), Handbook of Solid Waste Management, 2nd ed., McGraw-Hill, New York, 2002.
[3] L.-H. Chen, Y.-R. Chen, C.-Y. Chou, C.-H. Chen, C.-C. Ko, K.-L. Tung, Inorganic Membranes in Water and Wastewater Treatment, in: 2017. https://doi.org/10.1007/978-981-10-5623-9_5
[4] I. Abul Magd, State of the Environment 2017 Arab Republic of Egypt Summary for Policymakers Arab Republic of Egypt, 2017.
[5] A. Salim, I. Bakr, R. Saleh, A. Noor, Egypt-SOE-2019, Egypt, 2019.
[6] D. Salman, Industrial development and the trade-off to environment: Measurement techniques, meanings and outcomes in the context of water poverty in Egypt, International Journal of Green Economics. 5 (2011). https://doi.org/10.1504/IJGE.2011.039731
[7] I. Chiocchio, M. Mandrone, P. Tomasi, L. Marincich, F. Poli, Plant secondary metabolites: An opportunity for circular economy, Molecules. 26 (2021). https://doi.org/10.3390/molecules26020495
[8] A. Azmy, R. Ibrahim, E. Gohary, A.M. Azmy, R. El Gohary, Environmental and Sustainable Guidelines for Integrated Municipal Solid Waste Management in Egypt, 2017. https://www.researchgate.net/publication/320728195.
[9] M.A. Barakat, New trends in removing heavy metals from industrial wastewater, Arabian Journal of Chemistry. 4 (2011). https://doi.org/10.1016/j.arabjc.2010.07.019
[10] J. Gao, Membrane Separation Technology for Wastewater Treatment and its Study Progress and Development Trend, in: 2016. https://doi.org/10.2991/mmme-16.2016.202
[11] I.G. Wenten, Khoiruddin, Reverse osmosis applications: Prospect and challenges, Desalination. 391 (2016). https://doi.org/10.1016/j.desal.2015.12.011
[12] B. Belaissaoui, J. Claveria-Baro, A. Lorenzo-Hernando, D. Albarracin Zaidiza, E. Chabanon, C. Castel, S. Rode, D. Roizard, E. Favre, Potentialities of a dense skin hollow fiber membrane contactor for biogas purification by pressurized water absorption, J Memb Sci. 513 (2016). https://doi.org/10.1016/j.memsci.2016.04.037
[13] V.K. Thakur, S.I. Voicu, Recent advances in cellulose and chitosan-based membranes for water purification: A concise review, Carbohydr Polym. 146 (2016). https://doi.org/10.1016/j.carbpol.2016.03.030
[14] Z. Wu, C. Zhang, K. Peng, Q. Wang, Z. Wang, Hydrophilic/underwater superoleophobic graphene oxide membrane intercalated by TiO2 nanotubes for oil/water separation, Front Environ Sci Eng. 12 (2018). https://doi.org/10.1007/s11783-018-1042-y
[15] J. Liu, J. Yuan, Z. Ji, B. Wang, Y. Hao, X. Guo, Concentrating brine from seawater desalination process by nanofiltration-electrodialysis integrated membrane technology, Desalination. 390 (2016). https://doi.org/10.1016/j.desal.2016.03.012
[16] F. Yan, H. Chen, Y. Lü, Z. Lü, S. Yu, M. Liu, C. Gao, Improving the water permeability and antifouling property of thin-film composite polyamide nanofiltration membrane by modifying the active layer with triethanolamine, J Memb Sci. 513 (2016). https://doi.org/10.1016/j.memsci.2016.04.049
[17] N.P. Cheremisinoff, Handbook-of-Water-Waste-Water-Treatment-Technologies, Butterworth-Heinemann, USA, 2002.
[18] H.I. Abdel-Shafy, S.H. Abdel-Shafy, Membrane technology for water and wastewater management and application in Egypt, Egypt J Chem. 60 (2017). https://doi.org/10.21608/EJCHEM.2017.3480
[19] M.A.H. Bhuyan, R.K. Gebre, M.A.J. Finnilä, M. Illikainen, T. Luukkonen, Preparation of filter by alkali activation of blast furnace slag and its application for dye removal, J Environ Chem Eng. 10 (2022). https://doi.org/10.1016/j.jece.2021.107051
[20] M. Nodehi, V.M. Taghvaee, Alkali-Activated Materials and Geopolymer: a Review of Common Precursors and Activators Addressing Circular Economy, Circular Economy and Sustainability. 2 (2022). https://doi.org/10.1007/s43615-021-00029-w
[21] J. Davidovits, Geopolymer Chemistry and Applications, 5Th Ed. Geopolymer Institute. (2020).
[22] L. Zhang, Production of bricks from waste materials - A review, Constr Build Mater. 47 (2013). https://doi.org/10.1016/j.conbuildmat.2013.05.043
[23] L. Alves, A Quick Overview on Geopolymer Chemistry and General Properties, Research & Development in Material Science. 12 (2019). https://doi.org/10.31031/rdms.2019.12.000781
[24] G. Mucsi, M. Ambrus, Raw materials for geopolymerisation, in: MultiScience - XXXI. MicroCAD International Multidisciplinary Scientific Conference, 2017. https://doi.org/10.26649/musci.2017.008
[25] N.B. Singh, Fly ash-based geopolymer binder: A future construction material, Minerals. 8 (2018). https://doi.org/10.3390/min8070299
[26] S. Mabroum, S. Moukannaa, A. El Machi, Y. Taha, M. Benzaazoua, R. Hakkou, Mine wastes based geopolymers: A critical review, Clean Eng Technol. 1 (2020). https://doi.org/10.1016/J.CLET.2020.100014
[27] J. Singh, S.P. Singh, Geopolymerization of solid waste of non-ferrous metallurgy – A review, J Environ Manage. 251 (2019). https://doi.org/10.1016/j.jenvman.2019.109571
[28] M.F. Zawrah, R.A. Gado, N. Feltin, S. Ducourtieux, L. Devoille, Recycling and utilization assessment of waste fired clay bricks (Grog) with granulated blast-furnace slag for geopolymer production, Process Safety and Environmental Protection. 103 (2016). https://doi.org/10.1016/j.psep.2016.08.001

[29] C. Chen, M. xue Xu, X. Deng, Y. He, X. Cui, Preparation of metakaolin-based geopolymer membrane and its application in black liquor treatment, Appl Clay Sci. 232 (2023) 106773. https://doi.org/10.1016/J.CLAY.2022.106773

[30] S. Sanguanpak, W. Shongkittikul, C. Saengam, W. Chiemchaisri, C. Chiemchaisri, TiO2-immobilized porous geopolymer composite membrane for removal of antibiotics in hospital wastewater, Chemosphere. 307 (2022) 135760. https://doi.org/10.1016/J.CHEMOSPHERE.2022.135760

[31] N. Gamage, K. Liyanage, N. Gamage, K. Liyanage, S. Fragomeni, S. Setunge, Overview of different type of fly ash and their use as a building and construction material, in: International Conference of Structural Engineering, Sri Lanka, 2011. https://www.researchgate.net/publication/264707671.

[32] A. Dwivedi, M. Jain, A. Dwivedi, M.K. Jain, Fly ash–waste management and overview: A Review, Recent Research in Science and Technology. 6 (2014).

[33] A. Bhatt, S. Priyadarshini, A. Acharath Mohanakrishnan, A. Abri, M. Sattler, S. Techapaphawit, Physical, chemical, and geotechnical properties of coal fly ash: A global review, Case Studies in Construction Materials. 11 (2019). https://doi.org/10.1016/j.cscm.2019.e00263

[34] A.R.K. Gollakota, V. Volli, C.M. Shu, Progressive utilisation prospects of coal fly ash: A review, Science of the Total Environment. 672 (2019). https://doi.org/10.1016/j.scitotenv.2019.03.337

[35] J.M. Fox, Fly Ash Classification-Old and New Ideas, in: World of Coal Ash, 2017.

[36] P. He, F. Zhang, Y. Zhang, H. Chen, Multifunctional fly ash-based GO/geopolymer composite membrane for efficient oil-water separation and dye degradation, Ceram Int. 49 (2023) 1855–1864. https://doi.org/10.1016/J.CERAMINT.2022.09.149

[37] I. Yuksel, Blast-furnace slag, in: R. Siddique, P. Cachim (Eds.), Waste and Supplementary Cementitious Materials in Concrete, Woodhead Publishing Series in Civil and Structural Engineering, 2018: pp. 361–415. https://doi.org/10.1016/c2016-0-04037-8

[38] S.K. Malhotra, S.P. Tehri, Development of bricks from granulated blast furnace slag, Constr Build Mater. 10 (1996). https://doi.org/10.1016/0950-0618(95)00081-X

[39] M. Azarshab, F. Mohammadi, H. Maghsoodloorad, T. Mohammadi, Ceramic membrane synthesis based on alkali-activated blast furnace slag for separation of water from ethanol, Ceram Int. 42 (2016) 15568–15574. https://doi.org/10.1016/J.CERAMINT.2016.07.005

[40] F. Mohammadi, T. Mohammadi, Optimal conditions of porous ceramic membrane synthesis based on alkali-activated blast furnace slag using Taguchi method, Ceram Int. 43 (2017) 14369–14379. https://doi.org/10.1016/J.CERAMINT.2017.07.197

[41] T. Hertel, Y. Pontikes, Geopolymers, inorganic polymers, alkali-activated materials and hybrid binders from bauxite residue (red mud) – Putting things in perspective, J Clean Prod. 258 (2020) 120610. https://doi.org/10.1016/J.JCLEPRO.2020.120610

[42] R.J. Barla, S. Raghuvanshi, S. Gupta, Process integration for the biodiesel production from biomitigation of flue gases, Elsevier, 2022. https://doi.org/10.1016/B978-0-12-823958-2.00007-0

[43] S. Pacheco-Torgal, F. Abdollahnejad, Zahra Miraldo, M. Kheradmand, Alkali-Activated, Alkali-Activated Cement-Based Binders (AACB) as Durable and Materials : Some Shortcomings That Need to be Addressed, 2016. http://www.sciencedirect.com:5070/book/9780128045244/handbook-of-low-carbon-concrete (accessed October 22, 2023).

[44] A.A. Khalaf, K. Kopecskó, Properties of red-mud-based geopolymers in the light of their chemical composition, in: J Phys Conf Ser, Institute of Physics, 2022. https://doi.org/10.1088/1742-6596/2315/1/012024

[45] N. Ye, J. Yang, X. Ke, J. Zhu, Y. Li, C. Xiang, H. Wang, L. Li, B. Xiao, Synthesis and characterization of geopolymer from bayer red mud with thermal pretreatment, Journal of the American Ceramic Society. 97 (2014) 1652–1660. https://doi.org/10.1111/JACE.12840

[46] N. Koshy, K. Dondrob, L. Hu, Q. Wen, J.N. Meegoda, Mechanical Properties of Geopolymers Synthesized from Fly Ash and Red Mud under Ambient Conditions, (2019). https://doi.org/10.3390/cryst9110572

[47] D.K. Panesar, 3 - Supplementary cementing materials, in: S. Mindess (Ed.), Developments in the Formulation and Reinforcement of Concrete (Second Edition), Woodhead Publishing, 2019: pp. 55–85. https://doi.org/https://doi.org/10.1016/B978-0-08-102616-8.00003-4

[48] R. Siddique, Kunal, A. Mehta, Utilization of industrial by-products and natural ashes in mortar and concrete development of sustainable construction materials, in: Nonconventional and Vernacular Construction Materials: Characterisation, Properties and Applications, 2019. https://doi.org/10.1016/B978-0-08-102704-2.00011-1

[49] M. Soomro, V.W.Y. Tam, A.C. Jorge Evangelista, Industrial and agro-waste materials for use in recycled concrete, in: Recycled Concrete, 2023. https://doi.org/10.1016/b978-0-323-85210-4.00009-6

[50] Y. Silica, M. Ferreira, W. Dai, Y. Wang, Silica Fume Enhances the Mechanical Strength of Alkali-Activated Slag/Fly Ash Pastes Subjected to Elevated Temperatures, Fire 2023, Vol. 6, Page 252. 6 (2023) 252. https://doi.org/10.3390/FIRE6070252

[51] M.N. Qureshi, S. Ghosh, Effect of Si/Al ratio on engineering properties of alkali-activated GGBS pastes, Green Mater. 2 (2014) 123–131. https://doi.org/10.1680/GMAT.14.00001

[52] M. Youmoue, R. Théophile Tene Fongang, A. Gharzouni, R. Cyriaque Kaze, E. Kamseu, V.M. Sglavo, I. Tonle Kenfack, B. Nait-Ali, S. Rossignol, Effect of silica and lignocellulosic additives on the formation and the distribution of meso and macropores in foam metakaolin-based geopolymer filters for dyes and wastewater filtration, (123AD). https://doi.org/10.1007/s42452-020-2388-x

[53] P. Pavithra, M. Srinivasula Reddy, P. Dinakar, B. Hanumantha Rao, B.K. Satpathy, A.N. Mohanty, Effect of the Na 2 SiO 3 /NaOH Ratio and NaOH Molarity on the Synthesis of Fly Ash-Based Geopolymer Mortar, in: 2016. https://doi.org/10.1061/9780784480151.034

[54] A. Naveed, Noor-Ul-Amin, F. Saeed, M. Khraisheh, M. Al Bakri, S. Gul, Synthesis and characterization of fly ash based geopolymeric membrane for produced water treatment, Desalination Water Treat. 161 (2019). https://doi.org/10.5004/dwt.2019.24283

[55] S. Sanguanpak, A. Wannagon, C. Saengam, W. Chiemchaisri, C. Chiemchaisri, Porous metakaolin-based geopolymer granules for removal of ammonium in aqueous solution and anaerobically pretreated piggery wastewater, J Clean Prod. 297 (2021). https://doi.org/10.1016/j.jclepro.2021.126643

[56] A. Naveed, S. Gul, N. Ul Amin, M. Younas, N. Ullah, Synthesis and characterization of inorganic microfiltration membrane through geopolymerization, Desalination Water Treat. 66 (2017). https://doi.org/10.5004/dwt.2017.20212

[57] W.K.W. Lee, J.S.J. Van Deventer, The effect of ionic contaminants on the early-age properties of alkali-activated fly ash-based cements, n.d. https://doi.org/https://doi.org/10.1016/S0008-8846(01)00724-4

[58] M. xue Xu, Y. He, Z. han Liu, Z. fa Tong, X. min Cui, Preparation of geopolymer inorganic membrane and purification of pulp-papermaking green liquor, Appl Clay Sci. 168 (2019) 269–275. https://doi.org/10.1016/j.clay.2018.11.024

[59] T.H. Tan, K.H. Mo, S.H. Lai, T.C. Ling, Synthesis of porous geopolymer sphere for Ni(II) removal, Ceram Int. 47 (2021). https://doi.org/10.1016/j.ceramint.2021.06.268

[60] A. Naveed, F. Saeed, M. Khraisheh, M. Al Bakri, Noor-Ul-Amin, S. Gul, Porosity control of self-supported geopolymeric membrane through hydrogen peroxide and starch additives, Desalination Water Treat. 152 (2019) 11–15. https://doi.org/10.5004/DWT.2019.23895

[61] Y. Ge, Y. Yuan, K. Wang, Y. He, X. Cui, Preparation of geopolymer-based inorganic membrane for removing Ni2+ from wastewater, J Hazard Mater. 299 (2015). https://doi.org/10.1016/j.jhazmat.2015.08.006

[62] H. Castillo, H. Collado, T. Droguett, M. Vesely, P. Garrido, S. Palma, State of the art of geopolymers: A review, 22 (2022) 108–124. https://doi.org/doi:10.1515/epoly-2022-0015

[63] Z. Zhang, H. Yu, M. Xu, X. Cui, Preparation, characterization and application of geopolymer-based tubular inorganic membrane, Appl Clay Sci. 203 (2021). https://doi.org/10.1016/j.clay.2021.106001

[64] P.Y. He, Y.J. Zhang, H. Chen, Z.C. Han, L.C. Liu, Low-cost and facile synthesis of geopolymer-zeolite composite membrane for chromium(VI) separation from aqueous solution, J Hazard Mater. 392 (2020). https://doi.org/10.1016/j.jhazmat.2020.122359

[65] A.K. Basumatary, R.V. Kumar, A.K. Ghoshal, G. Pugazhenthi, Synthesis and characterization of MCM-41-ceramic composite membrane for the separation of chromic acid from aqueous solution, J Memb Sci. 475 (2015) 521–532. https://doi.org/10.1016/j.memsci.2014.10.055